Converter Design for a Model Solar Car

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Abstract

To provide our students with practical experience in power electronic design they undertake an assignment that involves a model solar car race. The students are required to design, build and demonstrate a dc-dc converter that matches the output from a 10W solar panel to a permanent magnet DC motor. The converter must step down the output voltage from the panel from 15V to 3V. This is a team-based assignment in which their mark is determined from an inspection, written report and a race. Such a project is important to stimulate the student's interest in power electronics as well as providing them with some practical power electronic design skills.

Introduction

To master power electronics, or in fact any sub discipline within electrical engineering, a student should demonstrate a proficiency in [1]:

- (a) factual knowledge;
- (b) knowledge of engineering procedures;
- (c) the ability to identify key concepts;
- (d) the ability to acquire new knowledge;
- (e) judgement to use incomplete / contradictory information.

The traditional lecture based course is good at testing the factual and engineering procedures knowledge, however it does not adequately address the other requirements. At the University of Canterbury there was the concern that some undergraduate students could complete two power electronic courses without any practical experience in power electronic design. Although, as part of the 24 lecture Year 3 power electronics course the students complete 8 hours of laboratory work, they only follow instructions on a laboratory sheet rather than thinking about the implications of building their own power electronic circuits. Neither do the laboratories provide the opportunity to gain an in-depth knowledge of the practical problems and limitations of power electronic circuit design. To remedy this situation the 48 lecture Year 4 power electronics course was changed in 1994 to make it more applications based. As part of this change the students undertake a practical power electronic design assignment that involves a model solar car race. The solar car project was selected because most students understand the application of a car, while the use of a solar panel provides an environmental focus to the project. Another important factor is that the solar panel produces safe voltage levels, which means the students can work independently on the project without direct supervision. In addition, the use of a solar panel places a severe restriction on the available power, which in turn forces the students to consider the efficiency of every aspect of their design.

Team-Based Project

The solar car project is structured as a team-based project. The students usually work in groups of two to ensure that they all experience some aspect of design, decision-making and teamwork. A team-based project means that the students also gain experience in managing a project, and communicating effectively with others. It has been found that having a team of two enables the students to bounce ideas off each other. This helps them to solve the problem more quickly or come up with an innovative solution to the problem. If the teams are made too large then there can be the situation in which some of the students will not fully participate and learn from the project.

As with any team-based project, there are teams comprised of good, capable students and teams with average to below-average students. The good teams usually get started immediately and construct an initial converter very quickly. This enables these teams to spend more of their time on optimising their design for the final race. The average to below-average student teams usually do not have much practical experience and knowledge, which impedes their progress and they might not have a fully working prototype by the end of the project. Most of the teams require guidance in how they should proceed with their project. This is achieved by covering relevant material in lectures which parallel the project, and by providing hints on how to solve particular problems they may have, rather than giving them the solution directly.

Project Details

The students are required to design, build and demonstrate a dc-dc converter that matches the output from a 10W solar panel to a permanent magnet DC motor (Figure 1). Each group is provided with a 10W solar panel mounted on an aluminium chassis along with the dc motor, a gearbox (7:1) and a servo for steering the vehicle (Figure 2). The servo is remotely controlled via a handheld radio link and is the only on-board item, which can be powered from an auxiliary battery source. Students are not allowed to alter any mechanical characteristics of the car and the problem can only be solved by designing and building electronics.

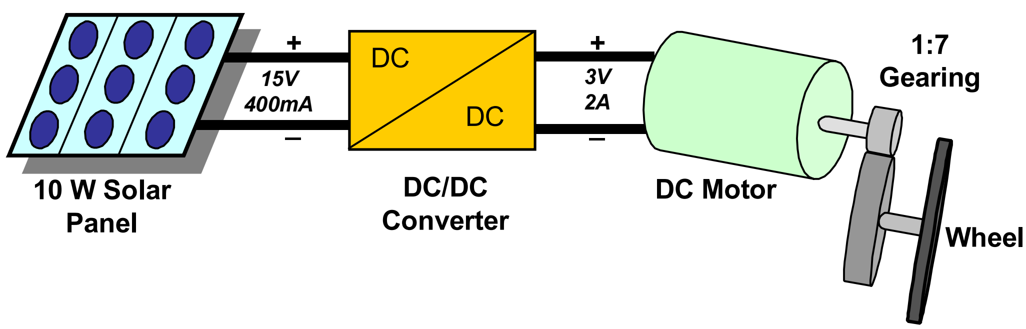
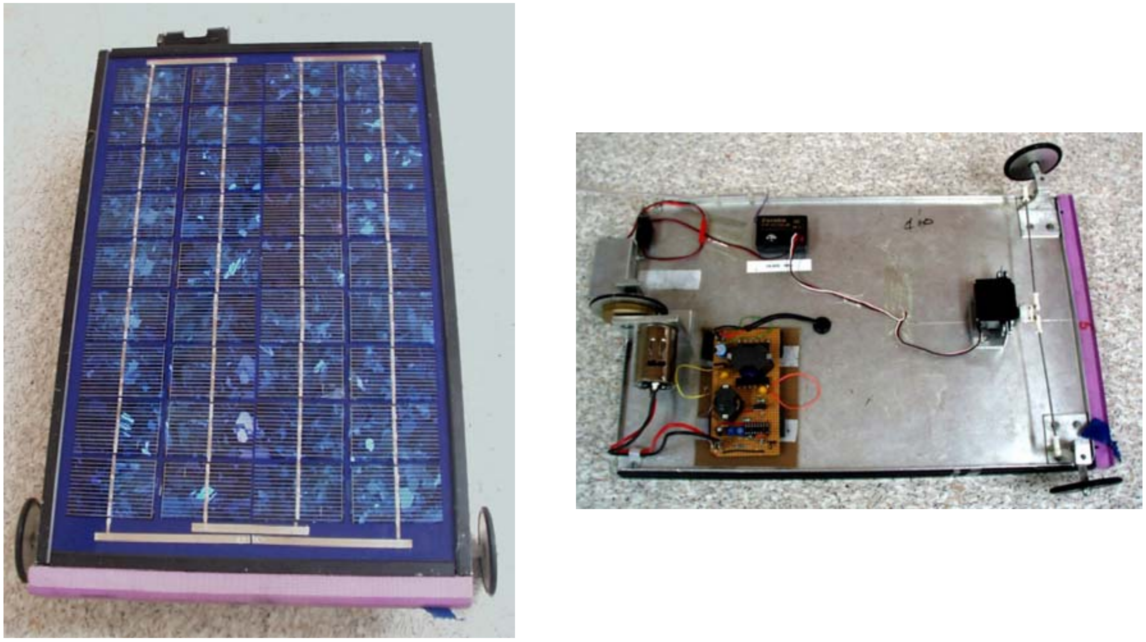


Figure 1: Model Solar Car System Block Diagram.

The solar panel and the DC motor have been deliberately selected so that there is an impedance mismatch. Therefore if the solar panel is directly connected to the motor the car would not move even under extreme sunlight conditions. The only way for the car to move is if power electronics is used. The solar panel has a 10W rating, but for the race (normally held in April) the maximum power the students will likely get is more like 6W. The output voltage of the panel is approximately 15V at a maximum current of 400mA. The motor can operate from a low voltage of 3V and draws around 2A on starting. Therefore a voltage step down ratio of 5:1 is required at start-up, but this requirement for high current soon disappears as the car gathers speed.

The objective is to have the fastest car on race day and the vehicle must be able to start moving under its own power as soon as sunlight falls on the panel. To achieve this objective two key design tasks have to be optimised; maximum power must be collected by the solar panel and transferred to the dc-dc converter, which in turn must transfer the power to the motor as efficiently as possible. Each year these are the basic instructions given to the class, but just to keep everyone honest an additional new requirement is added each year. For example, one year the specification may call for the cars to be reversible and the next the class is told that diodes are not allowed and the designs must resort to synchronous rectification.



Top View **Underside View**

Figure 2: Photograph of the Solar Car

The solution to the problem is essentially open-ended, average students achieve a good basic working design, while the better students have ample scope for improving efficiency of their converter or extracting that last bit of power from the solar panel. Even the weakest groups usually manage to get a design completed, which will at least partially satisfy the conditions of the race.

Detailed Converter Designs

Over the years that this project has run there has been a wide range of converter designs implemented. Each year a few groups, generally the weaker groups, will perhaps only get as far as implementing a simple chopper circuit. While the more able groups of students have produced some very sophisticated designs utilising push-pull and Cuk converters.

Before any detailed electronic design can take place each group must determine the DC motor and solar panel characteristics. To encourage each group to use their time wisely it is emphasised throughout that they must decide which characteristics they need to know and to focus their investigations on those characteristics. No extra credit is given for those groups which generate copious quantities of data, very little of which is pertinent to solving the problem at hand. In fact for this project the key characteristics required of the motor are its starting current and the terminal voltage required to produce maximum speed when the solar panel is operating at its maximum power point. Those groups that also make measurements of motor efficiency find to their dismay that the motor is typically about 40% efficient. Whoops, more than half of our available 6W of power from the solar panel has now suddenly disappeared. This really focuses their attention onto the electronics efficiency issues which arise later in the design process.

Most groups very quickly understand that they must try to operate the solar panel at its maximum power point for the duration of the race. Following a very simple set of experimental measurements to determine panel voltage and current (power) under various sunlight conditions, groups soon devise a simple strategy for control of the solar panel terminal voltage to maintain maximum output power from the panel. Typically maximum power can be obtained if the panel terminal voltage is maintained at about 15V.

Armed with this knowledge groups can now begin to consider their design in earnest. They soon realise that in order to meet the required motor starting current of about 2A the solar panel cannot deliver maximum power, but since starting is such a small proportion of the overall race, does it really matter?

So far the students have sufficient knowledge to determine the dc-dc converter transfer ratio required at start-up and also for running to produce maximum speed from maximum power. Some groups convince themselves that there will never be a need to boost the dc-dc converter output voltage beyond the 15V input voltage. While others will decide that to be able to boost the output voltage beyond 15V may be an advantage. The reality, after taking account of further losses is that the best anyone can actually achieve is about 12 – 13V and still be able to provide the required current to the motor. This is the stage where groups make their decisions on converter topology. Whatever their decision all groups are encouraged to go through the process of building a simple open-loop chopper first, adding filtering and converting it to a buck converter before launching into a full-scale highly sophisticated design. To initiate the practical phase of the project work all groups are given a copy of the data sheet for a low cost PWM control chip, TL494, and an associated laboratory sheet. The laboratory sheet takes them step-by-step through the process of setting up the PWM control chip on a breadboard and producing open-loop single and double-ended switching outputs. This simple exercise has proven to be a very valuable first step because it gets everyone started on some practical laboratory work and for some groups gets them over the fear of committing their ideas to hardware. The groups of capable students go through this phase quite quickly and progress onto their ultimate design goal without undue delay. The average to below-average groups on the other hand usually stall at this point, some only managing, in the long run, to produce a simple working example of an open-loop buck converter. Throughout this design and construction part of the project groups are encouraged to use simulation (usually Pspice) to test their design calculations.

The final steps in the design process relate to closing the control loop. The issue for each group is to decide what it really needs to control. Most groups eventually iterate to a decision to control the output voltage of the solar panel. This decision is based on the knowledge that maximum power can only be achieved at around 15V output, and it doesn't really matter how clever you are with the rest of the circuit if you aren't injecting maximum power into your converter then you simply won't achieve a very satisfactory outcome.

Design of the control loop provides a few surprises for many students. It is not the classical feedback control loop discussed in the textbooks, where an output is measured and compared to a reference to control an output. In this case, an input is measured and compared to a reference to control an input. This subtle difference is sufficient to force the students to carefully think through the logic of their control strategy. If the solar panel voltage rises for example, should the duty cycle rise or fall? How should the error amplifier be used? Is the reference connected to the positive or the negative input of the error amplifier?

Groups are instructed to build their converters on Vero board (Figure 3). Each board is attached to the underside of the car using Velcro strips. This allows boards to be attached and detached quickly and easily for testing and for races. They must provide standard push fit connectors for the connections to the solar panel and the DC motor. The example converter shown in Figure 3 also has wire loops which are added for the laboratory review so that currents can easily be sampled.

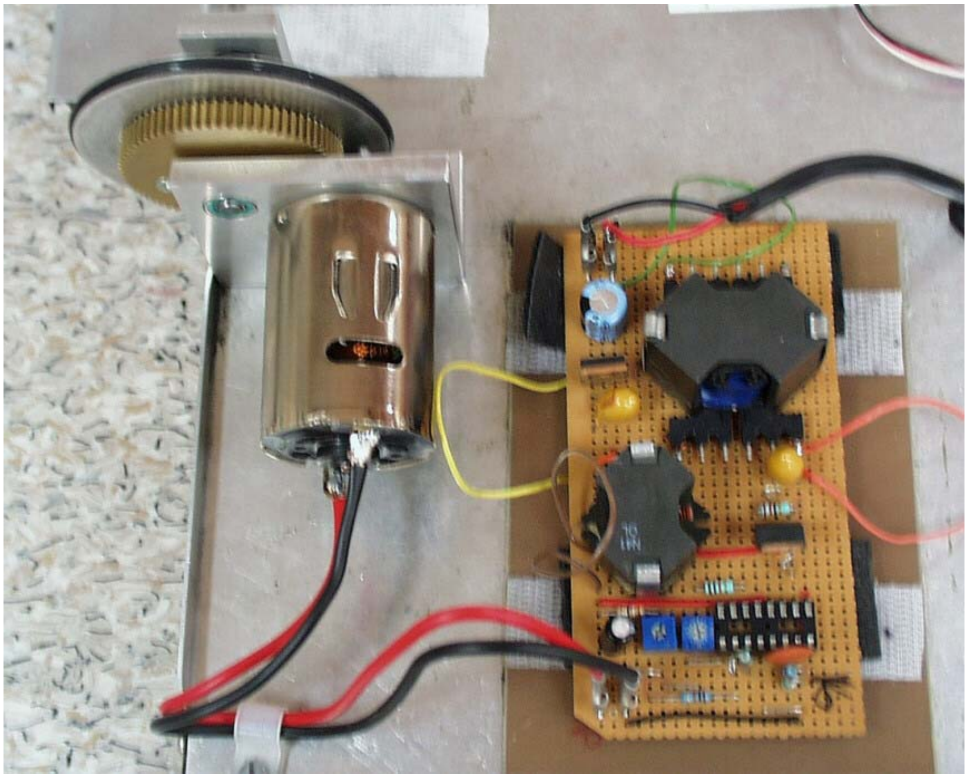


Figure 3: Sample converter

Assessment

This particular assignment nominally counts for 25% of the total course assessment. Three components make up this 25% assessment; a laboratory review worth 10%, an individual written report worth 15% and a group bonus mark of up to 5% awarded for the car's performance on race day. Thus there is the possibility of a student scoring 30% if they can manage to do extremely well in all aspects of the assessment. Typically this assignment runs over a six-week period and at the conclusion of week five each group is subjected to a laboratory review of their progress. They meet with the lecturer in the laboratory, bringing with them their hardware, a copy of their circuit diagram and their design notes. The 10% mark contribution from the laboratory review can only be achieved if the group has attempted to solve the problem including the new additional requirement for that year (e.g. car must be reversible, must use synchronous rectification). Weaker groups of students can opt not to attempt this and they then can only achieve a maximum mark of 5% from the laboratory review. From a list of previously published questions members of the group are asked to demonstrate their hardware and to answer questions about the performance of their hardware. Questions can be directed to each individual group member and even though a group mark is awarded for the laboratory review it is quickly obvious whether or not each individual understands what they are doing and the relative contributions of each group member can be readily assessed.

The emphasis on the assessment of the individual written report is on documentation of the design process, their understanding of that process and finally the evaluation of their design. A number of design decisions have to be made on the basis of incomplete or non-existent information. For example the DC motors have been rewound and no details of their new characteristics are provided at the start of the assignment. Each group must make their own decisions on the information about the motor, which they believe they need and devise a method of measurement. Manufacturer's data sheet for the 10W solar panel is provided, but as is often typical with engineering problems the data sheet does not provide the information, which is required to solve the problem at hand.

The bonus of up to 5% for the race (Figure 4) is allocated to each group on a very simple scale, ranging from 1% if the car starts under its own power on race day to 5% if a 1st or 2nd placing is gained in the final race of the day. The race has a low contribution to the overall assessment because other events such as poor mechanical reliability can have an impact on outcome of race and this can disadvantage the good students. Having the race as effectively a bonus 5% over and above the required 25% for the course assessment means that if the race has to be cancelled because of inclement weather the students can still achieve the full value of their 25% assessment. Luckily we have not had to cancel the race during the 8 years the project has run, although the students have been provided with some very challenging tests of their design skills on one or two occasions when the weather conditions have been marginal.

Figure 4: Race Day (3 April 2001)

Summary

Gregson and Little [1] identify ten characteristics of a good contest:

(a) is safe;
(b) requires increasing factual and procedural knowledge;
(c) requires exercising engineering judgement;
(d) fosters creativity;
(e) incorporates significant course material;
(f) provides success commensurate with care in design;
(g) permits many strategies with levels of success;
(h) does not require significant infrastructure;
(i) is easy to understand with simple scoring;
(j) should be a spectacle.

We believe we have achieved all of these characteristics in this assignment and over the years student feedback has confirmed that they believe the time spent on the assignment has been well worthwhile. In teaching and course surveys students have consistently rated this assignment highly as a learning experience and they often comment that it is an opportunity to bring some reality to the academic material presented in lectures and the textbooks. The race is a vital part of the success of this assignment, it is an important motivator and publicity tool. As race spectators Year 2 and 3 students see power electronics as being challenging and a fun learning experience, and want to be part of it. There is absolutely no doubt in our minds that this annual teaching project has had a very positive influence on student numbers and on their motivation to learn.

References

[1] Gregson P.H., Little T.A.: *Using Contests to Teach Design to EE Juniors*, IEEE Trans. on Education, vol. 42, August 1999, no. 3, pp. 229-32.